New experimental limit on Pauli Exclusion Principle violation by electrons (the VIP experiment)

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Abstract. The Pauli Exclusion Principle is one of the basic principles of modern physics and is at the very basis of our understanding of matter: thus it is fundamental importance to test the limits of its validity. Here we present the VIP (Violation of the Pauli Exclusion Principle) experiment, where we search for anomalous X-rays emitted by copper atoms in a conductor: any detection of these anomalous X-rays would mark a Pauli-forbidden transition. VIP is currently taking data at the Gran Sasso underground laboratories, and its scientific goal is to improve by at least four orders of magnitude the previous limit on the probability of Pauli violating transitions, bringing it into the $10^{-29 \div -30}$ region. First experimental results, together with future plans, are presented.

1. Introduction

The Pauli exclusion principle (PEP), which plays a fundamental role in our understanding of many physical and chemical phenomena, from the periodic table of elements, to the electric conductivity in metals, to the degeneracy pressure (which makes white dwarfs and neutron stars stable), is a consequence of the spin-statistics connection [1]. Although the principle has been spectacularly confirmed by the number and accuracy of its predictions, its foundation lies deep in the structure of quantum field theory and has defied all attempts to produce a simple proof, as nicely stressed by Feynman [2]. Given its basic standing in quantum theory, it seems appropriate to carry out precise tests of the PEP validity and, indeed, mainly in the last 15-20 years, several experiments have been performed to search for possible small violations [3, 4, 5, 6, 7, 8]. Often,

these experiments were born as by-products of experiments with a different objective (e.g., dark matter searches, proton decay, etc.), and most of the recent limits on the validity of PEP have been obtained for nuclei or nucleons.

In 1988 Ramberg and Snow [9] performed a dedicated experiment, searching for anomalous X-ray transitions, that would point to a small violation of PEP in a copper conductor. The result of the experiment was a probability $\frac{\beta^2}{2}<1.7\times10^{-26}$ that the PEP is violated by electrons. The VIP Collaboration set up an improved version of the Ramberg and Snow experiment, with a higher sensitivity apparatus [10]. Our final aim is to lower the PEP violation limit for electrons by $3 \div 4$ orders of magnitude, by using high resolution Charge-Coupled Devices (CCDs), as soft X-rays detectors [11, 12, 13, 14, 15], and decreasing the effect of background by a careful choice of the materials and shielding the apparatus from cosmic rays by setting it in the LNGS underground laboratory of the Italian Institute for Nuclear Physics (INFN).

In the next sections we describe the experimental setup, the outcome of a first measurement performed in the Frascati National Laboratories (LNF) of INFN in 2005, along with a brief discussion on the preliminary results obtained running VIP at the Gran Sasso National Laboratory (LNGS) of INFN.

2. The VIP experiment

The idea of the VIP (VIolation of the Pauli Exclusion Principle) experiment was originated by the availability of the DEAR (DAΦNE Exotic Atom Research) setup, after it had successfully completed its program at the DAΦNE collider at LNF-INFN [16]. DEAR used Charge-Coupled Devices (CCDs) as detectors in order to measure exotic atoms (kaonic nitrogen and kaonic hydrogen) X-ray transitions. CCDs are almost ideal detectors for X-rays measurement, due to their excellent background rejection capability, based on pattern recognition, and to their good energy resolution (320 eV FWHM at 8 keV in the present measurement).

Experimental method The experimental method, originally described in [9], consists in the introduction of new electrons into a copper strip, by circulating a current, and in the search for X-rays resulting from the forbidden radiative transition that occurs if one of the new electrons is captured by a copper atom and cascades down to the 1s state already filled by two electrons with opposite spins. The energy of this transition would differ from the normal K_α transition by about 300 eV (7.729 keV instead of 8.040 keV) [17], providing an unambiguous signal of the PEP violation. The measurement alternates periods without current in the copper strip, in order to evaluate the X-ray background in conditions where no PEP violating transitions are expected to occur, with periods in which current flows in the conductor, thus providing "fresh" electrons, which might possibly violate PEP.

The VIP setup The VIP setup consists of a copper cylinder with 45 mm radius, 50 μm thickness, 88 mm height, surrounded by 16 equally spaced CCDs of type 55 made by EEV [18]. The CCDs are at a distance of 23 mm from the copper cylinder, grouped in units of two chips, one above the other. The setup is enclosed in a vacuum chamber, and the CCDs are cooled to about 168 K by the use of a cryogenic system. The current flows in the thin cylinder made of ultrapure copper foil at the bottom of the vacuum chamber. The CCDs surround the cylinder and are supported by cooling fingers which are projected from the cooling heads in the upper part of the chamber. The CCDs readout electronics is just behind the cooling fingers; the signals are sent to amplifiers on the top of the chamber. The amplified signals are read out by ADC boards in the data acquisition computer. More details on the CCD-55 performance, as well on the analysis method used to reject background events, can be found in references [16, 19]. A schematic view of the setup is shown in fig. 1.

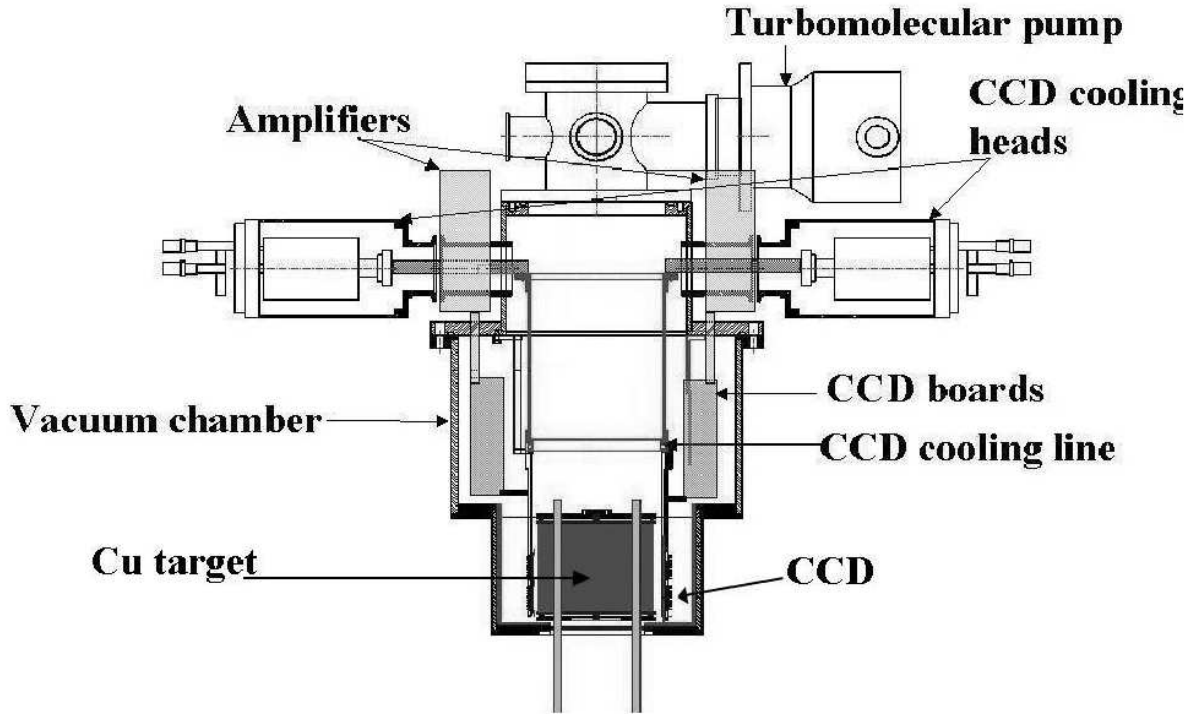

Figure 1. The VIP setup - schematic view

3. First VIP experimental results

The VIP setup is presently taking data in the low-background Gran Sasso underground laboratory of INFN. Before installation in the Gran Sasso laboratory, it was first prepared and tested in the LNF-INFN laboratory, where measurements were performed in the period 21 November - 13 December 2005. Two types of measurements were performed:

- 14510 minutes (about 10 days) of measurements with a 40 A current circulating in the copper target;
- 14510 minutes of measurements without current.

CCDs were read-out every 10 minutes. The resulting energy calibrated X-ray spectra are shown in figure 2. These spectra include data from 14 CCDs out of 16, because of noise problems in the remaining 2. Both spectra, apart of the continuous background component, display clear Cu K_α and K_β lines due to X-ray fluorescence caused by the cosmic ray background and natural radioactivity. No other lines are present and this reflects the careful choice of the materials used in the setup, as for example the high purity copper and high purity aluminium, the last one with K-complex transition energies below 2 keV. The subtracted spectrum is shown in Figure 3 a) (whole energy scale) and b) (a zoom on the region of interest). Notice that the subtracted spectrum is normalized to zero within statistical error, and is structureless. This not only yields an upper bound for a violation of the Pauli Exclusion Principle for electrons, but also confirms the correctness of the energy calibration procedure.

To determine the experimental limit on the probability that PEP is violated for electrons, $\frac{\beta^2}{2}$, from our data, we used the same arguments of Ramberg and Snow: see references [9] and [20] for details of the analysis. The obtained value is:

$$\frac{\beta^2}{2} < 4.5 \times 10^{-28} \tag{1}$$

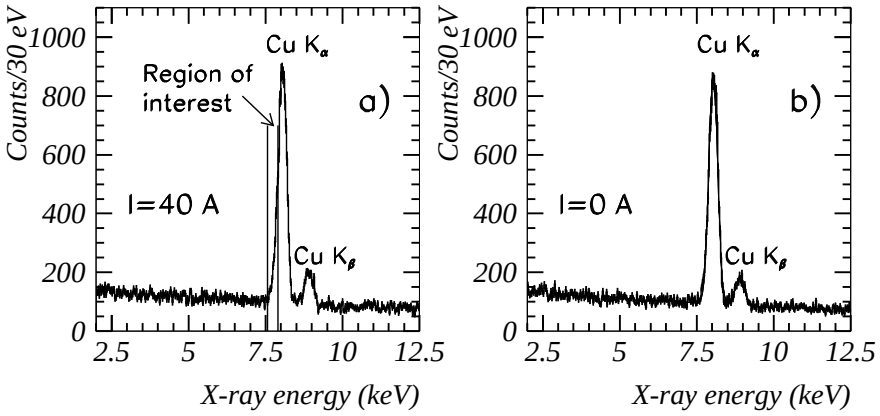

Figure 2. Energy spectra with the VIP setup in laboratory: (a) with current (I = 40 A); (b) without current (I = 0).

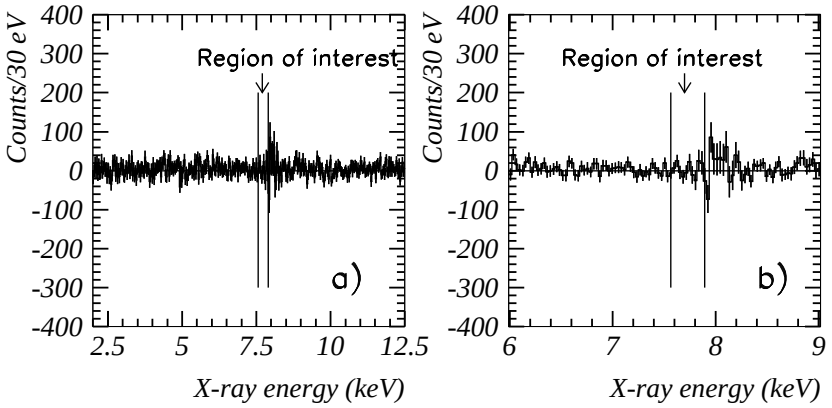

Figure 3. Subtracted energy spectra in the Frascati measurement, current minus no-current, giving the limit on PEP violation for electrons: a) whole energy range; b) expanded view in the region of interest (7.564 - 7.894 keV). No evidence for a peak in the region of interest is found.

We have thus improved the limit obtained by Ramberg and Snow by a factor about 40.

4. Preliminary LNGS updated results

In order to reduce the background, the apparatus is currently installed in the LNGS underground laboratory, to reduce cosmic rays interactions, while the effects of natural radioactivity are moderated by a massive shield built by low activity materials, as it is shown in figures 4 and 5). At the time of writing, about one year of data have been analyzed, in the above-mentioned acquisition conditions. Our data consist of two periods of data acquisition:

- about 236005 minutes of measurements with a 40 A current in the copper target;

- about 172685 minutes of measurements without current.

where CCDs were read-out every 10 minutes. Performing the analysis as described in the previous section, from the subtracted spectra we find the new preliminary value for the violation parameter:

$$\frac{\beta^2}{2} \leq 6.0 \times 10^{-29} \tag{2}$$

improving the limit obtained by Ramberg and Snow by a factor about 250. Today this is the best value ever reached on the probability of PEP violation for the electrons.

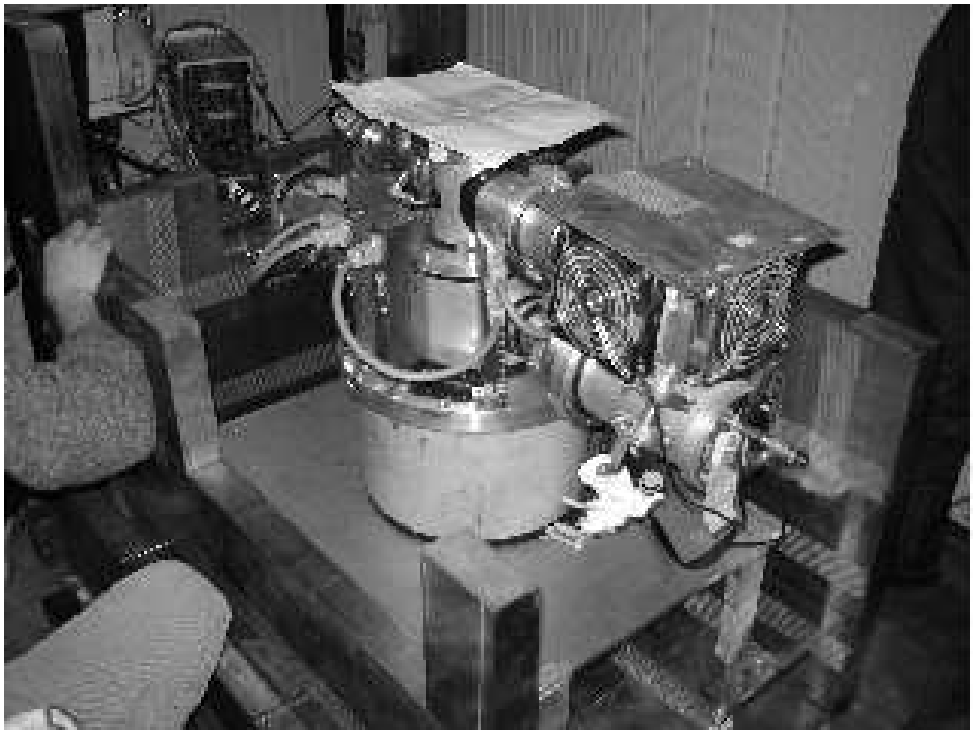

Figure 4. Installation of the VIP setup in Gran Sasso underground laboratory

5. Conclusions and perspectives

A new measurement of the PEP violation limit for electrons is being performed by the VIP experiment. The search of a tiny violation is based on a measurement of PEP violating X-ray transitions in copper, under a circulating 40 A current. A new limit for the PEP violation for electrons was established: 4.5×10^{-28}, lowering by about two orders of magnitude the previous one [20]. We have installed VIP at LNGS in spring 2006 and started the data-taking in reduced background condition. After one year of data taking the LNGS preliminary limit for the PEP violation for electrons was lowered to 6.0×10^{-29}, about three orders of magnitude better than the Ramberg and Snow experiment [9]. Data acquisition will continue at LNGS with the goal of bringing the limit on PEP violation for electrons into the 10^{-30} region, which is of particular interest [21] for all those theories related to possible PEP violation coming from new physics.

Figure 5. The VIP setup taking data at the Gran Sasso underground laboratory

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